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Simultaneous generation of violet, blue, and green lasers using Nd:YAl$_3$(BO$_3$)$_4$ channel waveguides under pumping at 815 nm

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Violet, blue, and green lasers were simultaneously generated by nonlinear processes using ultrafast laser inscribed neodymium-doped yttrium aluminum borate (Nd:YAl$_3$(BO$_3$)$_4$ or Nd:YAB) channel waveguides under pumping at 815 nm. These visible lasers were generated by the frequency doubling, self-frequency summing, and self-frequency doubling processes based on a 1062 nm laser radiation that corresponded to the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition of Nd^{3+} ions. Further, the wavelength tunability for the violet and blue lasers was achieved by simply tuning the pump wavelength within the $^4I_{9/2} \rightarrow {}^4F_{5/2}$ transition. The results obtained indicate that Nd:YAB waveguides are promising candidates for efficient compact visible laser sources.

1 Introduction The design and development of compact visible laser sources has attracted much attention owing to their numerous applications in a great variety of fields such as laser printing, undersea communications, medicine, biophotonics, and lighting display. The most popular design scheme for a visible laser source is hybrid crystal, where both the gain medium and nonlinear crystal approaches have been used to achieve high power visible-light radiation. The laser-gain and non-linear media are used for the generation of infrared and visible laser radiations, respectively [1–4]. However, this approach needs the use of two different materials, and therefore, it has a complicated structure, which limits the compactness of the final device. Hence, materials used for self-frequency conversion are much more interesting due to its potential application for more compact devices [5–9].

Ultrafast laser inscription (ULI) of waveguides modifies the local refractive index of optical materials in a controlled manner. Thus, it has been extensively used for the fabrication of integrated laser sources in optical materials [10–14]. A reduction in active laser area produces large light intensities in the waveguide, leading to low-threshold laser oscillations. ULI of waveguides is also convenient for frequency-conversion processes requiring high intensity radiations. ULI of frequency-mixing waveguides has been already demonstrated in hybrid structures in an optical block (diffusion-bonded nonlinear crystals). The ULI waveguide fabricated in such a nonlinear material was capable of generating green laser lights by the self-frequency doubling (SFD) process of 1.06 μm laser radiation of Nd^{3+} ions [15]. Although this experimental approach is interesting and novel, it suffered from a decrease in mechanical resistance of the diffusion-bonded bulk material and the optical losses derived from the ultrafast laser writing of waveguides in two different materials with different optical properties (refractive index). All these drawbacks could be avoided if the ULI waveguide is fabricated using a single optical material with good infrared laser properties and high nonlinear coefficients, so that both the laser and frequency mixing processes could be feasible in a single waveguide. Such waveguides are known as self-frequency conversion (SFC) laser waveguides. The previous studies on SFC laser waveguides focused on the SFD effect, i.e., the second harmonic generation of the fundamental infrared laser line leading to visible laser radiation. In addition to the SFD process, the self-frequency-sum mixing (SFSM) process is also possible and is of great interest to examine its effect on visible laser light generation. SFSM generates short wavelength radiations by nonlinear mixing of both laser and pump radiations. In the case of neodymium-doped SFC crystals, SFSM has been used in the past for tunable blue light generation [8]. Despite its potential in the development of ultra-compact blue lasers, SFSM in ULI channel waveguides have not been studied. Among the different SFC optical materials where ULI waveguides have been already demonstrated, neodymium-doped yttrium aluminum borate ($Nd:YAl_3(BO_3)_4$ or Nd:YAB) is of special relevance, because this system has both excellent nonlinear and fluorescence properties due to the presence of a YAB matrix and neodymium (high emission cross section and absorption coefficients at 815 nm), respectively. This unique combination of Nd and YAB makes Nd:YAB waveguides a paradigm among the different SFC crystals. In fact, the SFD process in a Nd:YAB ULI waveguide has been recently demonstrated based on Type II waveguides capable of light confinement under both ordinary and extraordinary polarizations [16]. Despite the success in green laser light generation using ULI waveguides by the SFD process, an integrated blue laser light source from Nd:YAB ULI waveguides by SFSM of pump and laser radiations has not been developed yet.

In this study, violet, green, and blue laser lights were observed in the Nd:YAB waveguide structure through frequency doubling (FD), SFD, and SFSM processes using 1062 nm infrared laser radiation and simultaneous pumping at ~810 nm. The channel waveguides were fabricated using femtosecond (fs) laser writing of "double line" Type II waveguides. Based on the waveguide structure, the wavelength of blue and violet lasers were tuned by changing the pump laser in the wavelength range of 800–830 nm. The maximum power outputs of laser lights with a pumping power of ~95 mW are 62.5 μW (408 nm), 20 μW (461 nm), and 19 μW (531 nm). Thus, this study provides a hint for further design of compact multi-wavelength visible laser light sources.

2 Experiments The Nd:YAB (doped by 5% Nd^{3+} ions) crystal used in this study was 4.8 mm long, and it was cut at $\theta = 35^\circ$ angle with respect to the optical axis, consisting of the Type I phase-matching direction for the SFSM of laser at 1062 nm under pumping at 815 nm. The channel waveguide in the crystal was fabricated by femtosecond-laser inscription by using the "double-line" approach. This approach has been successfully applied to fabricate channel waveguides in many other optical substrates. The femtosecond beam (120 fs pulse duration, 795 nm central wavelength, and 1 kHz repetition rate) was focused by a 20× microscope objective, 150 μm beneath the sample surface. Pairs of parallel set of damage tracks, with 15–25 μm separation, were thus inscribed on the crystal by scanning the sample at different velocities (15–25 μm/s) and pulse energies in the range 0.34–1.01 μJ. The optimum parameters for the best performance of the waveguide were found to be as follows: (i) a 20 μm separation between tracks, (ii) a scanning velocity of 15 μm/s, and (iii) a pulse energy of 0.68 μJ.

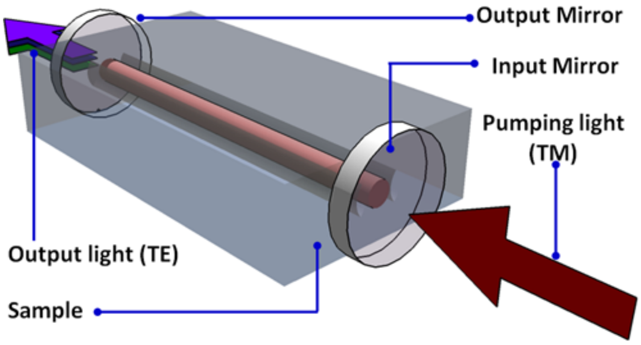

Figure 1 Schematic plot of the experimental setup for the multi-wavelength visible laser radiation from the double-line waveguide based on the Nd:YAB crystal.

The propagation loss of the Nd:YAB waveguide was measured by the Fabry–Perot method [17] according to different wavelengths of detecting light. In the near-infrared and visible light region, the propagation loss of the waveguide was found to be 1 dB/cm and 1.5 dB/cm at a wavelength of 1064 nm and 632.8 nm, respectively.

The waveguide laser experiments were performed by using a conventional end face coupling system, as shown in Fig. 1. During the experiment, a pump laser (modulated between 800 nm and 830 nm) from a continuous wave (cw) Ti:sapphire laser (Coherent MBR 110) was coupled to the waveguide through a specially designed convex lens ($f = 25$ mm). The output light from the opposite facet was collected using a long working distance microscope objective (×20, NA = 0.4). Two laser mirrors were mechanically attached to both faces of the sample to achieve laser oscillations in the waveguide. The input mirror has a high reflectivity (>99.5%) and transmittance (99%) at 1062 nm and ~815 nm, respectively. The output mirror has a reflectivity >99.8% and transmittance >95% at 1062 and 400–550 (visible range) nm, respectively. At the same time, a prism was used to divide the output light to different wavelengths. The spectrum of the output light generated from the channel waveguide was detected by a 2 nm spectral resolution spectrograph.

3 Results and discussion The measured spectrum of output light obtained under pumping at ~815 nm with an absorbed power of 95 mW is also shown in Fig. 2. Within the near-infrared region, the most intense emission was

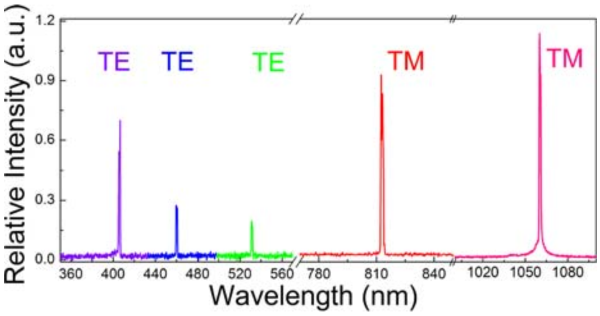

Figure 2 Laser emission spectrum of the Nd:YAB waveguide laser under pumping at 815 nm.

seen at 1062 nm corresponding to the infrared-laser oscillation of Nd ions. In the visible-light region, three lines were observed at ~407.5 nm (violet), 461.1 nm (blue), and 531 nm (green), with a full-width at half maximum (FWHM) of 1 nm. As the pumping wavelength varies from 800 to 830 nm, the wavelength of violet and blue lights changes accordingly, whereas that of green light remains constant. On the other hand, transverse-magnetic (TM) and transverse-electric (TE) polarizations of waveguide modes were obtained in the infrared and visible spectral ranges, respectively. To analyze the nonlinear processes in the waveguide, the relationship between wavelength of visible and pumping lights was summarized, as shown in Fig. 3.

Figure 3(a) shows the wavelength of the blue line, as a function of the pumping wavelength. The blue light wavelength varies from 456 to 465 nm, as the pumping wavelength varies from 800–830 nm. This blue laser light is supposed to arise from the SFSM in the waveguide structure because the cutting direction of this sample is along the Type I phase-matching of pump and laser radiations. The relationship between the blue light and pumping wavelengths is expressed by Eq. (1) (energy conservation). The dashed green line in Fig. 3(a) shows the fitting of the experimental data to Eq. (1) with an uncertainty error <1 nm.

$$\frac{1}{\lambda_{\text{blue}}} = \frac{1}{\lambda_{1062}} + \frac{1}{\lambda_{\text{pump}}} . \tag{1}$$

Figure 3(b) shows the variation of violet laser light wavelength as a function of the pumping wavelength. At 829 nm pumping, the maximum wavelength of violet light is ~415 nm. Further, at 797 nm pumping, the minimum wavelength of violet light is ~399 nm. The relationship between the violet light and pumping wavelengths is expressed by Eq. (2), which indicates that the violet light arises from the FD process of the pumping light. The dashed red line in Fig. 3(b) shows the fitting of experimental data to Eq. (2) with an uncertainty error <1 nm. Moreover, the polarization switch is also consistent with the Type I phase-matching direction (from TM pumping to TE violet laser), which further supports the fact that the violet laser light was generated by a FD process,

$$\lambda_{\text{violet}} = \frac{1}{2} \lambda_{\text{pump}} . \tag{2}$$

For the green laser light, the wavelength remains stable as the pumping wavelength is varied, and it equals to half of the infrared laser oscillation of Nd^{3+} ions (~1062 nm). Considering both the wavelength and polarization conversions, it demonstrates almost the same behavior of the SFD process as described in literature [16]. Therefore, it was concluded that the SFD (green light), FD (violet light), and SFSM (blue light) processes occurred simultaneously in this waveguide structure.

Based on the Sellmeier equation given in Ref. [8], the phase-matching angle for these nonlinear processes were calculated. As shown in Fig. 3(c), the values obtained are as follows: 30°, 35°, and 41° corresponding to the SFD (815–531 nm), SFSM (815 nm and 1062–461 nm), and FD (815–407.5 nm) processes, respectively. In this study, the sample was cut at $\theta = 35°$ angle with respect to the optical axis. This phase-matching direction is consistent with that of the SFSM process and ~11° mismatching of the FD and SFD processes were observed.

It has been proved that the frequency conversion also occurred with slightly phase mismatching, although the efficiency was reduced [5–7]. However, this phenomenon was not observed in Ref. [8], where the authors used the same crystal as in this study. The waveguide can induce higher light intensity as compared to the bulk laser setup with the same power input, and the behaviour of nonlinear effects has close relationship with the light intensity. Therefore, the enhanced nonlinear effect observed in this study should be attributed to the special characteristics of the waveguide structure.

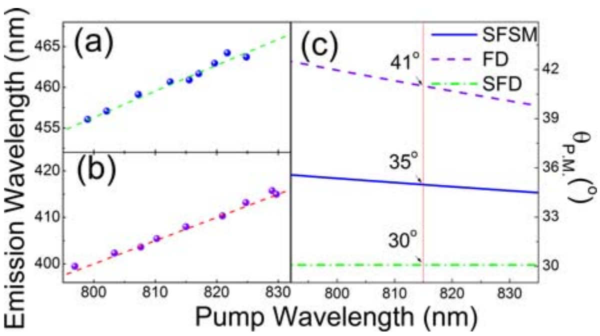

Figure 3 Wavelength of (a) blue and (b) violet laser lights are shown, as functions of pumping laser wavelength (blue and violet dots). The green and red lines are the best fitting of experimental data to Eqs. (1) and (2). (c) Phase-matching directions for the SFSM (solid blue line), FD (dashed violet line), and SFD (dash-dotted green line) processes as a function of pumping wavelength.

Figure 4 shows the plots of violet (a), green (b), and blue (c) laser powers versus the absorbed pumping powers at 815 nm. The thresholds for the blue and green lasers are ~42 mW of absorbed power above the infrared 1062 nm

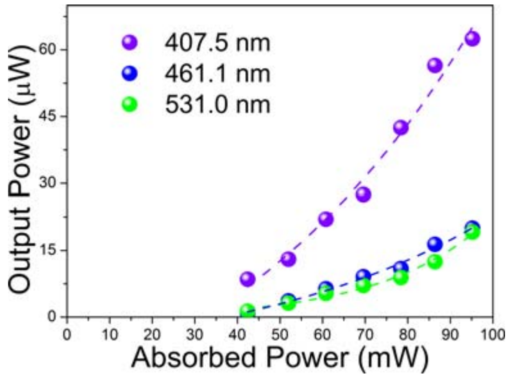

Figure 4 Output power of violet, blue, and green lasers as a function of the absorbed power at a wavelength of 815 nm.

laser threshold of ~10 mW. The maximum power output of green and blue lights are ~20 μW corresponding to the slope efficiency of 0.035%. The violet light could be observed even with an absorption power far less than 40 mW, which is generated by the FD process of pumping light. Compared to the maximum output power of the three visible lights, the value for violet light is ~3 times higher than the other two with respect to the slope efficiency of 0.1%. It is because the power of the pumping light is much higher than 1062 nm laser, which mainly contributed to the generation of blue and green laser lights. Please note, the transmission of the output mirror is ~5% at the wavelength of 400 nm–550 nm, which indicates much higher energy of generated visible light in the cavity.

4 Conclusions In summary, the violet, blue, and green laser radiations were observed simultaneously through the SF, SFSM, and SFD processes in the Nd:YAB crystal waveguide owing to the enhanced nonlinear effect by the waveguide structure. The wavelength of violet and blue laser lights can be tuned from 400 to 418 nm and 456 to 465 nm, respectively. This study gives a hint for further development of more compact and tunable visible laser sources for photonic applications.

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